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Low Cost Digital Image Photogrammetry

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ABSTRACT

A problem in modular shipbuilding is the lack of a reliable, low cost method of obtaining and utilizing dimensional control in 3D . Photogrammetry has been successfully used as a tool for this application, but because of the large number of systematic errors associated with film-based cameras, only very large shipyards are using this. Recently, developments in Charge Coupled Device (CCD) imaging arrays for cameras have allowed some success in applying photogrammetric techniques in dimensional control. Main stream photogrammetric software and hardware configurations have been expensive and complicated. Digital camera systems and computers were purchased and programmed to tie existing inexpensive software packages with Geometric Dilution of Control (GDOP) error propagation analysis, originally designed for topographic mapping, into a tool for production shipyard fabrication dimensional control.

NOMENCLATURE

CCD Charge-Coupled Device
GDOP Geometric Dilution of Precision

INTRODUCTION

A major shortcoming in the shipbuilding industry is the lack of a reliable method of obtaining three-dimensional measurements of complex parts during fabrication and fitting to other parts. Photogrammetry has been successfully used as a tool for this application, but because of the large number of systematic errors associated with film-based cameras, only very large shipyards are using it because of the complexity of the film-based problem.[1] The requirements have been for expensive and exotic photogrammetric instruments, expensive proprietary special-purpose software packages, heavy training requirements for a multi-disciplinary staff, etc.[2] Furthermore, film-based photogrammetric systems tend to be on the slow end of the spectrum of dimensional-control systems. For quick turn-around time for results back to the workers in the shipyard, film-based photogrammetry has not been effective.

Recently, developments in Charge Coupled Device (CCD) imaging arrays for cameras have allowed some success in applying photogrammetric techniques without film in dimensional control. Previously classified technology for high-resolution CCD arrays has become available on the open market, but the existing film-based software has still been quite expensive. Digital camera systems and computers were purchased and configured to tie existing inexpensive software packages with Geometric Dilution of Precision (GDOP) error propagation originally designed for topographic mapping into a tool for production shipyard fabrication dimensional control. The availability of GDOP is a critical distinction for photogrammetric software. Most photogrammetry packages, both in the public domain (free) as well as commercial, have only rudimentary indicators of adjustment quality (errors) and commonly give only root-mean-square (rms) values for the fit of object space control. PC GIANT© performs an error propagation analysis of the geometric dilution of precision for every point in an adjustment, including the unknown points being solved. The presentation of GDOP results in the form of eigenvectors/eigenvalues allows the shipyard analyst to inspect the accuracy of each and every individual point identified for fitting. Graphical screen plots of positional errors presented as ellipses are an easy check to verify consistency of results; blunders and large errors become instantly evident. GDOP allows for a constant and consistent quality check for accuracy control.

The Kodak ™ DCS 460 cameras (Figure 1) are the most expensive component of the system developed. Presently, the cameras cost approximately $29,000 each, plus an additional $10,000 to include all the requisite accessories (multiple lenses, radio remote-control, tripod, case, etc.). The reliability of the three cameras

Figure 1

has been flawless except for one faulty battery that was replaced within 24 hours. The cameras seem to be completely acceptable for heavy day-to-day use in a shipyard environment.

However, the software will cost less than $3,000 per seat. Total single system cost is under $35,000.

TEST APPLICATIONS

Five separate digital photogrammetry test applications were initiated (the first three were at Avondale Shipyards) consisting of a shell bolster model, a mid-body section, a plate-cutting shop and an "as-built" machinery site.

Shell Bolster Model. Photographs were taken of a scale model at a shipyard. Images were imported to the Desktop Mapping System (DMS ®) mensuration software. The GDOP error analysis results appeared good, but initial reaction by Avondale personnel indicated that discrepancies existed. It was discovered that the discrepancies were due to the poor identification of the pin-prick targets utilized.

Double Hull Mid-body Tanker Section. Plans were made to use the digital camera system in providing dimensional control after an existing ship stern was cut for later mating to a new mid-body section and bow. Results appear promising. Large (25 mm (1 in.)diameter) day glow targets were used in daylight at a distance of approximately 27 meters (88 feet) with complete success.

Plate Shop / Factory. There was concern at Avondale Shipyards about their numerically-controlled flame cutting tables with respect to differential movement of large steel plates (24 mm thick x 6 m x 18 m)(1-inch thick x 20ft x 60ft) being cut. The remote control three-camera system was ideally suited for such an investigation to determine how much movement exists and when and where it occurs. Three cameras were set up and exposures were shot at 10-minute intervals for 2 hours; the period required to cut the subject steel plate. The electronic flashes were quite adequate for the distances which were less than 60 m (200 ft), but the orientation of the target points (flat retro-reflective tape stickers) were at too shallow an angle to permit sufficient light to return to all of the cameras. The results were inconclusive because of camera exposures of the target points. Initial results of target design research can be improved upon by using magnets and ball-bearings painted with various retro-reflective materials.

As Built Industrial Site. Wink Engineering collaborated with respect to an industrial As Built experiment which demonstrated 6 mm accuracy easily achieved over 10 m. Retro-reflective targets were used indoors with a electronic flash. The GDOP indicates that 10 meters is not a limiting size.

Tugboat Hull Offsets. A project was to quickly determine the "as-built" hull offsets of a tugboat inside of a dry dock. The project was a success with only one-half day of field work. Retro-reflective targets were used in daylight with electronic flash. Accuracy achieved was 8 mm (1/3 – inch) in the X-Y plane (more or less parallel to the deck) and 6 mm (1/4 inch) in the Z component (vertical) for a vessel over 30 m (100 feet) long.

OBJECTIVE

The shipyard system is capable of being used in production demonstrations as well as serving as a model configuration of components easily assembled by individual shipyards throughout the United States. The primary objective is to provide a demonstrable system that consists of standard (state-of-the-art) hardware components, standard (state-of-the-art) software components, and a minimum of customizing. Nothing in this research is especially new in concept except that system costs have plummeted. Technology has progressed in PC-based image processing, PC-based photogrammetry and digital camera design. Old ideas that were extremely difficult to implement are now well within reach of any shipyard in need of reliable, high-volume dimensional control. The system is intended to demonstrate that a single technician (with one or two helpers) can provide near real-time 3D dimensional control in a production shipyard environment. By minimizing the use of drydock time, the competitiveness of U.S. shipyards can be enhanced with the most advanced CCD cameras available for unclassified applications.

METHODOLOGY

The accuracies stated herein are as reported by the photogrammetric solution through the rigorous least squares adjustment of observed parameters and the GDOP. A variance-covariance matrix for each set of parameters is determined from the inverse of the normal equation. This is then multiplied by the estimate of variance of unit weight. The standard deviation for each element is the square root of the diagonal terms of that matrix.

The Variance of Unit Weight may be estimated by the equation:

$$\sigma_o^2 = \frac{\Sigma(v_i \quad w_i \quad v_i)}{(n-u)} \qquad (1)$$

where,

v_i	is the residual of the i^{th} observation,
w_i	is the weight,
n	is the number of observations,
u	is the number of 'unknowns' or 'solvable parameters', and
(n-u)	is the degrees of freedom.

In the photogrammetric problem the number (n) of observations is equal to the number of plate components; one for x and one for y, or two times the number of image points measured. Add to this the number of measurements for object space coordinates. One for each of the known components (X,Y,Z). Depending on the external source of information, camera station position (X_C ,Y_C,Z_C) and orientation elements azimuth, elevation, swing (α, h, s) as well; they can be added to the number of observations as six times the number of camera stations. Although these are considered as solvable parameters, they can also be treated as weighted observations if sufficient information is available.

The unknowns or solvable parameters (u) are the object space control positions. For each unique point in the adjustment, three unknowns are counted. Camera station position (X_c,Y_c,Z_c) and orientation elements (α,h,s) are commonly considered 'unknowns', giving rise to additional numbers of unknowns equal to six times the number of camera stations.

To summarize,

v = the output residual for each observation,
w = input weight which may be thought of as
$1/\sigma 2$ for each observation,
n = total number of observations,
m = 2 * number of plate measurements.,
c = 1 for each object space component,
s = 6 * number of camera stations.

The six camera parameters are always treated as unknowns; however, depending on the external source of information, these may also be treated as weighted observations contributing to the number of direct weighted observation equations. When the weights of the direct observations are small, the camera parameters may be treated as completely free and no contribution is then made to the direct weighted observations.

p = 3 * number of points (X_G,Y_G,Z_G). Note: one, two or three of these components may have also been counted as observations under 'c'.

Again, the estimate of variance of unit weight is defined as the summation of the input weights ($1/\sigma 2$) multiplied by the output residuals squared ($v2$). If all is perfect,

$$\frac{\Sigma v^2}{\sigma^2} = (n-u) \qquad (2)$$

for all observations. This summation, when divided by the degrees of freedom (the number of observations minus the number of parameters) results in a value close to 1.00.

For a two-dimensional case,[3] we consider the bivariate normal distribution then for random error components only:

$$\left(\frac{x}{\sigma_x}\right) - 2\_(\text{xover} \quad \sigma_x)\left(\frac{y}{\sigma_y}\right)^2 = (1-\_^2)c^2 \qquad (3)$$

This represents a family of error ellipses centered on the origin of the X,Y coordinate system. When c = 1, this is the standard error ellipse. The size, shape and orientation of the standard error ellipse are governed by the distribution parameters σ_x, σ_y, and ϱ.

Six examples illustrating the effects of different combinations of error distribution parameters are shown in Figure 2

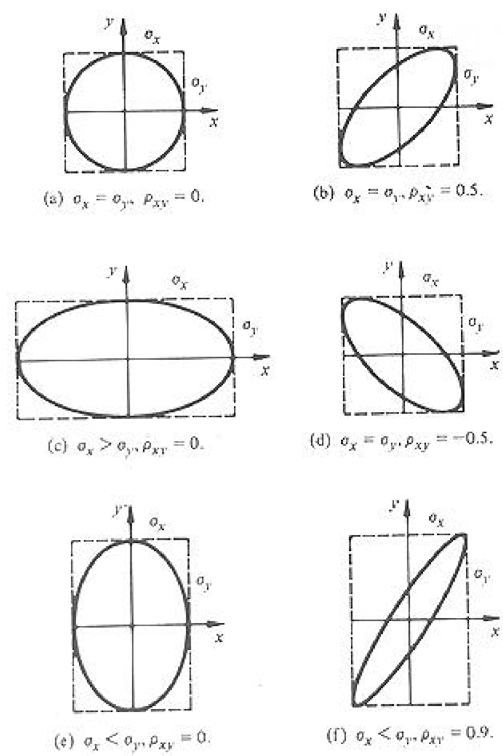

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Figure 2

Note that these figures represent the various effects of a bias as the result of the least squares adjustment of random error. What is most desirable is a result equivalent to ellipse (a) - no bias such that the error figure is equal in all directions - a circle. The further we depart from a circle, the less desirable the result in that a significant bias is displayed**.**

Ellipse (f), then, is the least desirable for a position determination. A shipbuilder is given a quality check tool that on the surface can be viewed as a subjective criterion. The choice of the appropriate math model for the photogrammetric adjustment offers a solid mathematical foundation for the graphical review of "goodness of fit." In surveying, all measurements are made with some degree of error. With an error propagation for the geometric dilution of precision (GDOP) in a 3D analytical photogrammetric adjustment of observations, the result is a realistic estimate of the reliability of measurements. There is less reliance on "experience" and a greater assurance of an objective estimator of the quality of the observations, quality of dimensions and quality of the fabrication accuracy control.

A typical standard error ellipse in the X-Y plane is shown in Figure 3:

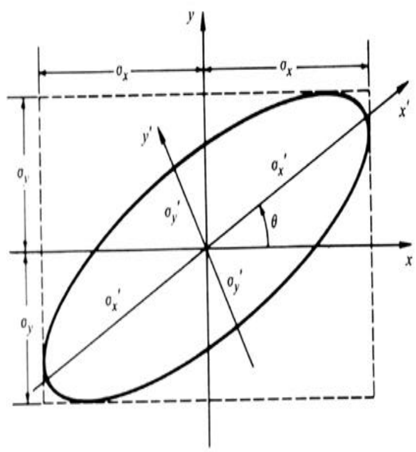


Figure 3

Since c = 1, the imaginary box (broken line) that encloses the ellipse has half-dimensions σ_x and σ_y. In general, the principal axes of the ellipse, x' and y' do not coincide with the coordinate axes X and Y; the major axis of the ellipse, x' makes an angle θ with the X-axis. A positional error is expressed in the x,y coordinate system by random vector [X',Y']. The covariance matrices for random vectors

$$\begin{bmatrix} \mathbf{X} \\ \mathbf{Y} \end{bmatrix}, \begin{bmatrix} \mathbf{X}^1 \\ \mathbf{Y}^1 \end{bmatrix} \qquad (4)$$

are

$$\begin{bmatrix} \boldsymbol{\sigma}_{\mathbf{x}}^2 & \boldsymbol{\sigma}_{\mathbf{xy}} \\ \boldsymbol{\sigma}_{\mathbf{xy}} & \boldsymbol{\sigma}_{\mathbf{y}}^2 \end{bmatrix} \begin{bmatrix} \boldsymbol{\sigma}_{\mathbf{x}}^2 & 0 \\ 0 & \boldsymbol{\sigma}_{\mathbf{y}}^2 \end{bmatrix} \quad (5)$$

respectively. The off-diagonal terms in the covariance matrix for $\begin{bmatrix} \mathbf{X}^1 \\ \mathbf{Y}^1 \end{bmatrix}$ are zero because X' and Y' are uncorrelated (x' and y' are the principal axes of the ellipse).

Applying the general law of propagation of variances and covariances[4] to the vector relationship given previously:

$$\begin{bmatrix} \boldsymbol{\sigma}_{\mathbf{x}}^2 & 0 \\ 0 & \boldsymbol{\sigma}_{\mathbf{y}}^2 \end{bmatrix} = \begin{bmatrix} \cos\boldsymbol{\theta} & \sin\boldsymbol{\theta} \\ -\sin\boldsymbol{\theta} & \cos\boldsymbol{\theta} \end{bmatrix} \begin{bmatrix} \boldsymbol{\sigma}_{\mathbf{x}}^2 & \boldsymbol{\sigma}_{\mathbf{xy}} \\ \boldsymbol{\sigma}_{\mathbf{xy}} & \boldsymbol{\sigma}_{\mathbf{y}}^2 \end{bmatrix} \begin{bmatrix} \cos\boldsymbol{\theta} & -\sin\boldsymbol{\theta} \\ \sin\boldsymbol{\theta} & \cos\boldsymbol{\theta} \end{bmatrix} \qquad (5)$$

Multiplying the matrices and equating corresponding elements,

$$\boldsymbol{\sigma}_{\mathbf{x}}^2 = \boldsymbol{\sigma}_{\mathbf{x}}^2 \cos^2\boldsymbol{\theta} + 2\boldsymbol{\sigma}_{\mathbf{xy}} \sin\boldsymbol{\theta}\cos\boldsymbol{\theta} + \boldsymbol{\sigma}_{\mathbf{y}}^2 \sin^2\boldsymbol{\theta} \quad (6)$$

$$\boldsymbol{\sigma}_{\mathbf{y}}^2 = \boldsymbol{\sigma}_{\mathbf{x}}^2 \sin^2\boldsymbol{\theta} + 2\boldsymbol{\sigma}_{\mathbf{xy}} \sin\boldsymbol{\theta}\cos\boldsymbol{\theta} + \boldsymbol{\sigma}_{\mathbf{y}}^2 \cos^2\boldsymbol{\theta} \quad (7)$$

$$0 = (\boldsymbol{\sigma}_{\mathbf{y}}^2 - \boldsymbol{\sigma}_{\mathbf{x}}^2)\sin\boldsymbol{\theta}\cos\boldsymbol{\theta} + \boldsymbol{\sigma}_{\mathbf{xy}}(\cos^2\boldsymbol{\theta} - \sin^2\boldsymbol{\theta}) \quad (8)$$

Substituting (1/2) sin 2θ for sinθ cosθ, and cos 2θ for (cos2 θ - sin2 θ),

$$\frac{1}{2}(\boldsymbol{\sigma}_{\mathbf{y}}^2 - \boldsymbol{\sigma}_{\mathbf{x}}^2)\sin 2\boldsymbol{\theta} + \boldsymbol{\sigma}_{\mathbf{xy}} \cos 2\boldsymbol{\theta} = 0 \quad (9)$$

from which:

$$\tan 2\boldsymbol{\theta} = \frac{2\boldsymbol{\sigma}_{\mathbf{xy}}}{\boldsymbol{\sigma}_{\mathbf{x}}^2 - \boldsymbol{\sigma}_{\mathbf{y}}^2} \quad (10)$$

The quadrant of 2θ is determined in the usual way from the signs of the numerator $2\theta_{xy}$ and denominator (σ_{x2} - σ_{y2}). Eliminating θ results in the following expressions for the variances of X' and Y':

$$\boldsymbol{\sigma}_{\mathbf{x}}^2 = \frac{\boldsymbol{\sigma}_{\mathbf{x}}^2 + \boldsymbol{\sigma}_{\mathbf{y}}^2}{2} \left[\frac{(\boldsymbol{\sigma}_{\mathbf{x}}^2 - \boldsymbol{\sigma}_{\mathbf{y}}^2)^2}{4} + \boldsymbol{\sigma}_{\mathbf{xy}}^2 \right]^{\frac{1}{2}} \quad (11)$$

$$\boldsymbol{\sigma}_{\mathbf{y}}^2 = \frac{\boldsymbol{\sigma}_{\mathbf{x}}^2 + \boldsymbol{\sigma}_{\mathbf{y}}^2}{2} - \left[\frac{(\boldsymbol{\sigma}_{\mathbf{x}}^2 - \boldsymbol{\sigma}_{\mathbf{y}}^2)^2}{4} + \boldsymbol{\sigma}_{\mathbf{xy}}^2 \right]^{\frac{1}{2}} \quad (12)$$

The standard deviations $\sigma_{x'}$, and $\sigma_{y;}$ are the semi-major axis and semi-minor axis, respectively, of the standard error ellipse. Furthermore, the variances $\sigma 2_{x'}$ and $\sigma 2_{y§}$ are the eigen values of the covariance matrix of the random vector $\begin{bmatrix} \mathbf{X} \\ \mathbf{Y} \end{bmatrix}$.

For the three-dimensional case as provided by a photogrammetric solution, the eigen vectors are provided in the form of a 3X3 matrix of direction cosines for each point and the

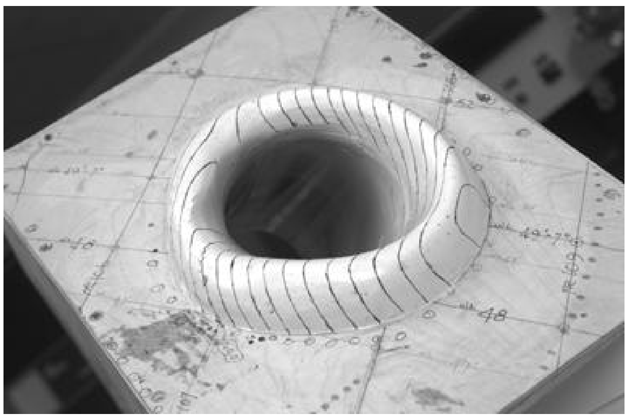
eigen values are provided for each component (σ_x,σ_y ,σ_z). Graphics software provides 2-D views for the X-Y plane, X-Z plane and the Y-Z plane.

DISCUSSION OF RESULTS

Active participation with a shipyard included:

Shell Bolster Model. Photographs were taken of a scale model (Figure 4) with good geometry and good tonal range. Images were imported to the Desktop Mapping System (DMS®) software. The analysis results appeared good, but initial reaction by shipyard personnel indicated

Figure 4



that discrepancies existed. The actual targets were holes made in the surface of the model by a drafting compass needle. The sizes of the holes varied under magnification, the material around many of the holes were craterous and when the results of the photogrammetric analysis were perused, the units were expressed at full scale. Whatever discrepancies do exist are due to the difficulty in the identification of the photogrammetric targets available. The preparation of the model was intended for mechanical 3D digitization which was used with acceptable results. Although a different method of marking targets might be used in the future for such models, the use of digital photogrammetry is probably inappropriate when mechanical 3D digitizers are accessible.

Double Hull Mid-Body Tanker Section. Informational photographs were taken of a mid-body section under fabrication (Figure 5).

Figure 5

Plans have been made to use the digital camera system in providing dimensional control after an existing ship is cut for later mating to the new mid-body section. As of the end of the period of funded research for this project, the existing ship stern had just been photographed in the dry dock.. Tests were made for target visibility with excellent results. Camera distance was about 27 meters (88 feet) from the mating surface of the stern section, and a 28mm wide-angle lens was used. This particular focal length of lens was chosen because of the physical constraints imposed by the size of the interior of the dry dock. Targets used were office-style labels 32 mm (11/4") round. The beige ship color required a "red glow" target color for contrast. The shipyard made a cherry picker available for the photography session (Figure 6).

The "Red Glow" target stickers were placed (one hour) at the locations where coordinates were desired by the Accuracy Control Section. Photos were taken at nine locations with 100% overlap such that practically every control point and unknown point ("pass point")

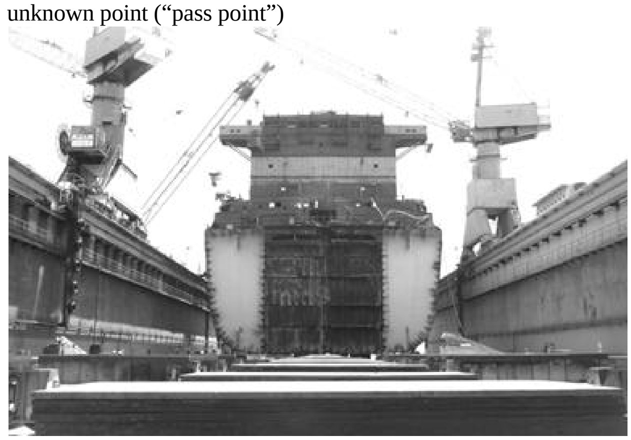


Figure 6

appeared in each of the nine convergent photos. Resulting accuracy's were X= $\pm$4 mm (0.16 inches), Y= $\pm$11 mm (0.433 inches), Z= $\pm$4 mm (0.14 inches) (four hours for analysis) and were deemed acceptable (Appendix A).

Plate Shop / Factory. There is some concern at shipyards with the numerically-controlled flame cutting tables with respect to

differential movement of large steel plates 25mm x 6 m x 18 m (1 inch thick x 20 ft x 60 ft) being cut. Sometimes these steel plates move during cutting, other times they don't. The three-camera system with simultaneous remote control is ideally suited for such an investigation to determine how much movement exists and when & where it occurs. A visit to the plate shop / factory was made and control was established by the Accuracy Control Department. Three cameras were set up, and 3 simultaneous exposures were shot at 10-minute intervals for 2 hours, the period required to cut the subject steel plate (Figure 7).

Figure 7

The results were inconclusive because of camera exposures of the target points. The standard electronic flash units were quite adequate for the distances of less than 61 m (200 feet), but the orientation of the target points (flat retro-reflective tape stickers) were at too shallow an angle to permit sufficient light to return to the camera. (Stickers that were oriented perpendicular to the camera & strobe lights showed up with spectacular light returns at distances exceeding 60 m.) Experiments were initiated to develop retro-reflective targets that would be adequate for such distances and for any angle of incidence. Initial results of target design research can be improved upon by using magnets and ball-bearings painted with various retro-reflective materials. Initially, ball bearings were painted with highway sign reflective paint. The quality of the targets was poor because of the viscous nature of the paint that had glass beads held in suspension. On recommendation from a professional sign painter's supply store, targets were then painted with white primer. In an attempt to replicate the aluminum layer of reflective tape, the targets were then sprayed with a splattered aluminum paint. The targets were then sprayed with aerosol adhesive and coated with spherical glass beads. The resultant targets appear promising.

In addition to the three projects initiated with the shipyard collaboration, two additional projects were completed with potential for shipbuilding applications:

Figure 8

Industrial "As-Built 3D CAD Model." An industrial facility under construction was chosen for a pilot project, and was targeted and surveyed in two hours by two surveyors (Figure 8). The target points were flat retro-reflective circular tape stickers with rectangular tabs attached for ID notes (one hour) (Figure 9). The control consisted of approximately 12 points surveyed to an accuracy of better than 1.6 mm (0.06 inches) in X-Y-Z. The photogrammetric solution included 19 photographs with 2 different focal length lenses. Results were satisfactory and were generally within the requisite accuracy of 6 mm (0.25 inches) in X-Y-Z. The computed coordinates were delivered in the form of a final report. The photogrammetric solution took 16 man-hours. Retro-fitting new equipment into an existing engine room is an application of this easily-implemented technique. The site survey requires only the technician and the camera.

Figure 9

"As-Built" Tugboat Hull Offsets. A Naval Architect needed to determine the "as-built" dimensions of an existing tugboat (M/V J.K. McLean) in order to compute the stability characteristics of the vessel. Desired overall accuracy was ±12 mm (0.5 inches) for all three components (X-Y-Z), and speed of measurement was a major concern in order to *minimize the changes for dry dock rental time* (Figure 10).

Figure 10

The vessel was available at 12:30 p.m., and three men started targeting the bulkhead locations with 10 mm (0.41 inch) diameter reflective tape. The targeting operation took a total of four and a half hours. Four object space control points were surveyed with the aid of a 30 m (100 foot) steel tape and an automatic level. The X-Y-Z control was completed in 15 minutes. A total of 52 photographs were taken with electronic flash in 15 minutes. Total dry dock time was 5 hours. Of the 52 photos taken, 26 were actually used in the photogrammetric analysis. Photogrammetric analysis time totalled 48 hours because of two blunders - one blunder in the reduction of the object space control points of approximately 0.33 m (1 foot), one blunder because of duplicate point identifications assigned during the measurement phase. Thirty seven hours were because of human error; actual productive work would have taken about 12 hours if there were no blunders. Final accuracy was ±8 mm (0.33 inches) in X (lengthwise along the keel), ±9 mm (0.35 inches) in Y (width offsets perpendicular to the keel) and ±5 mm (0.20 inches) in Z (vertical). The blunders were made in the office and were corrected in the office.

CONCLUSIONS

Digital image photogrammetry is a system that is reliable and easily implemented with "off-the-shelf" equipment and inexpensive topographic mapping software. Higher accuracy's can be obtained by modeling more sources of systematic error such as lens distortion. Greater functionality can be obtained from the system by customizing the topographic mapping software to a more specific shipbuilding context; specifically with respect to units of measurement and reference conventions. A phototriangulation software package that computes the error propagation of the Geometric Dilution of Precision is a necessity for reliable production Quality Checks.

RECOMMENDATIONS

The results demonstrated that existing inexpensive topographic mapping software with GDOP error propagation analysis can be used with high-resolution CCD cameras for shipbuilding and industrial 3D "as-built" applications. It is recommended that work continue for target design, software to easily connect applications, and to develop a training package to facilitate technology transfer of inexpensive terrestrial photogrammetry software & techniques to the U.S. Shipbuilding Industry.

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